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A RECONFIGURABLE OPTICAL SWITCH

Related Application

This application is related to copending U.S. Application Serial No. 09/571,833 entitled "A Reconfigurable Optical Switch," filed in the United States Patent and Trademark Office on May 16, 2000.

Field Of The Invention

The invention relates generally to an optical communications system and more particularly to an optical switch for flexibly routing light in a wavelength-selective manner.

Background Of The Invention

Significant interest exists in multi-wavelength communication systems, which are typically referred to as Wavelength Division Multiplexed (WDM) systems. These systems use a WDM optical signal having different wavelength components that support different streams of information. While WDM systems were initially investigated to increase the information capacity that a fiber could transmit between two points, recent improvements in optical filtering technology, among other things, has led to the development of switching elements which allow a complex network of paths to be constructed that differ from wavelength to wavelength. Furthermore, in addition to the availability of wavelength dependent switching elements in which a given wavelength is routed along a given path, reconfigurable optical elements have become available. Such reconfigurable optical elements can dynamically change the path along which a given wavelength is routed to effectively reconstruct the topology of the network as necessary to accommodate a change in demand or to restore services around a network failure.

Examples of reconfigurable optical elements include Optical Add/Drop Multiplexers (OADM) and Optical Cross-Connects (OXC). OADMs are used to separate or drop one or more wavelength components from a WDM signal, which

is then directed onto a different path. In some cases the dropped wavelengths are directed onto a common fiber path and in other cases each dropped wavelength is directed onto its own fiber path. OXCs are more flexible devices than OADMs, which can redistribute in virtually any arrangement the components of multiple WDM input signals onto any number of output paths.

The functionality of the previously mentioned reconfigurable optical elements can be achieved with a variety of different devices. For example, a common approach employs any of a number of different broadband switching fabrics inserted between a pair of demultiplexers/multiplexers. Examples of OADM elements are disclosed in U.S. Patent Nos. 5,504,827, 5,612,805, and 5,959,749, and general OXC switching architecture is reviewed by E. Murphy in chapter 10 of Optical Fiber Telecommunications IIIB, edited by T. Koch and I. Kaminow. As shown in these references, these approaches sequentially demultiplex the wavelengths, perform the necessary switching and then remultiplex, where the OXC can direct a given wavelength onto any output because a conventional OXC uses a relatively complex MxM device for the switching fabric, while OADMs are less flexible due to their use of an array of 2x2 optical switches that can only direct between one of two outputs. Two alternate approaches to OADMs employ switchable mirrors effectively inserted between a device that simultaneously performs wavelength demultiplexing and multiplexing. The first of these approaches uses a thin film dielectric demultiplexer/multiplexer that is traversed twice by the wavelengths (e.g., U.S. Pat. No. 5,974,207), while the second approach uses dispersion from a bulk diffraction grating to demultiplex (separate) the wavelength channels before they reflect off an array of tiltable mirrors (U.S. Patent No. 5,960,133). Another set of OADM technologies employ 4-port devices that drop multiple wavelengths onto a single fiber output in a reconfigurable manner, and thus require an additional demultiplexer if the channels need to undergo broadband optoelectronic conversion at the receiver. One realization of such functionality uses fiber optic circulators added to a two-port version of the previously described diffraction grating demultiplexer and tiltable mirror array (Ford et al., Postdeadline papers LEOS '97,

IEEE Lasers and Electro-Optics Society). A second realization uses integrated silica waveguide technology (e.g., Doerr, IEEE Phot. Tech. Lett '98) with thermo-optic phase shifters to switch between the add and drop states for each wavelength. Another four-port OADM employs a fiber optic circulator and an optional tunable fiber grating reflector to route the dropped channels (e.g., C. R. Giles, IOOC '95, JDS 2000 catalog)

All of the aforementioned conventional optical switching technologies have shortcomings. These devices generally fall into two classes with respect to their shortcomings: very flexible devices with high cost and high optical loss, and lower flexibility devices, which are less expensive and have lower optical loss. The most flexible OXCs can be programmed to switch the path of any of a large number of wavelengths, each onto its own fiber (e.g. demux/mux with switches), however these devices may have up to 20 dB of insertion loss and therefore require an optical amplifier to compensate for the loss. This substantially adds to the cost of an already expensive device. Because these devices are so costly, less flexible alternatives such as fiber gratings and thin film filters are often used. While these devices have a significantly lower cost and insertion loss (2-5 dB/node), they are typically less flexible because they are implemented as fixed wavelength OADMs that cannot be reconfigured. These devices are also inflexible because as you scale them so that they drop more wavelengths their loss, cost, size and/or complexity increase to the point that the more flexible OXC alternatives become more attractive. Recently, as shown in U.S. Patent No. 5,479,082, some flexibility has been added to these lowest cost OADM devices so that they can selectively drop or pass a predetermined subset of wavelengths that was previously designated as fixed. In addition, the previously described reconfigurable OADM devices offer somewhat enhanced flexibility, but typically at the expense of higher insertion loss (for Demux/switches), limited wavelength resolution (for bulk grating approaches), and/or higher cost for additional Mux/Demux equipment used in connection with four-port devices.

One particular limitation of the conventional OXC and OADM approaches, which demultiplex the incoming signal before optical switching is performed, is

that each output port can only drop a particular fixed wavelength that cannot be altered. In this configuration each switch is arranged so that it only receives a preselected wavelength component from the demultiplexer, and therefore can only output that particular wavelength. Unless subsequent optical switching is used, the flexibility of these devices is limited since it is not possible to redirect a given wavelength from one output port to another output port or to redirect multiple wavelengths to a given output port, should that become necessary. This is true not only for WDM switches but also broadband switches generally, including 1xM broadband switches such as shown in U.S. Patent No. 5,621,829, for example. This functionality is desirable when a unique element within the network is accessible through a particular port, and it is desirable to (a) change the wavelength channel directed to that port, or (b) direct additional wavelengths over that particular fiber accessed via that port. Two situations where this functionality proves useful is when a link needs to be restored using an alternate wavelength, or when the information capacity directed to a specific port needs to be increased by adding additional WDM wavelengths down the same fiber.

Copending U.S. Application Serial No.09/571,833 entitled "A Reconfigurable Optical Switch," filed in the U.S.P.T.O on May 16, 2000, discloses an optical switching element that achieves the previously mentioned functionality. That is, this switching element can direct each and every wavelength component of a WDM signal from any input port to any output port independently of one another. More specifically, this optical switch, similar to most current optical switches, provides an optical path between two subsets of the total optical ports, which are conventionally denoted "input" and "output" ports. This optical switch can only provide connections between the subset of input ports and the subset of output ports, or vice versa, but it cannot provide a connection between two ports within the same subset (either input or output). That is, in this switch, there are usually two distinct subset of ports; once light enters one subset, it must exit from the other subset. Unfortunately, this limitation prevents a wavelength component from being routed between two ports in the same subset of ports. Such a capability would be advantageous, for example, in bi-directional systems when a

customer wishes to communicate between two premises by connecting through the output ports of a remote distribution node, thereby circumventing an unnecessary portion of the optical network. While it would be desirable to provide this functionality in a broadband, wavelength independent switch, it would be even more advantageous to provide such functionality for each and every wavelength of a WDM signal in a wavelength-dependent switch.

Accordingly, there is a need for an optical switching element in which each and every wavelength component can be directed from any given port to any other port without constraint.

Summary Of The Invention

In accordance with the present invention, an optical switch is provided which includes a plurality of input/output ports for receiving one or more wavelength component(s) of an optical signal. The optical switch also includes an optical arrangement that directs the wavelength component to any given one of the plurality of input/output ports. The given input/output port may be selected from among any of the plurality of input/output ports.

In accordance with one aspect of the invention, the optical arrangement retroreflects the wavelength component to the given input/output port.

In accordance with another aspect of the invention, the optical signal includes a plurality of wavelength components and the optical arrangement includes at least one wavelength selective element. The wavelength selective element selects one of the wavelength components from among the plurality of wavelength components. The optical arrangement also includes a plurality of optical elements each associated with one of the wavelength selective elements. Each of the optical elements direct the selected wavelength component, which is selected by its associated selective element, to a given one of the plurality of input/output ports independently of every other wavelength component.

In accordance with yet another aspect of the invention, the wavelength selective elements may be thin film filters each transmitting therethrough a different one of the wavelength components and reflecting the remaining

wavelength components. Alternatively, the wavelength selective elements may be bulk diffraction gratings.

In accordance with another aspect of the invention, the optical elements are reflective mirrors that are selectively tiltable in a plurality of positions such that in each of the positions the mirrors reflect the wavelength component incident thereon to any selected one of the input/output ports.

In accordance with another aspect of the invention, the reflective mirrors are part of a micro-electromechanical (MEM) retroreflective mirror assembly. The retroreflective mirror assembly may include an aspheric lens or a curved reflector element.

In accordance with another aspect of the invention, the optical switch includes a free space region disposed between the input/output ports and the optical arrangement.

In accordance with another aspect of the invention, the free space region includes an optically transparent substrate having first and second parallel surfaces. In this case, the plurality of wavelength selective elements are arranged in first and second arrays which extend along the first and second parallel surfaces, respectively.

In accordance with yet another aspect of the invention, the first and second arrays are laterally offset with respect to one another. Each of the wavelength selective elements arranged in the first array direct the selected wavelength component to another of the wavelength selective elements arranged in the second array.

In accordance with yet another aspect of the invention, the optically transparent substrate may include air as a medium in which the optical signal propagates. Alternatively, the optically transparent substrate may be silica glass.

In accordance with another aspect of the invention, a method is provided for directing at least the first and second wavelength components of a WDM signal, which includes a plurality of wavelength components, from a first input/output port to any selected one of a plurality of input/output ports. The plurality of input/output ports includes the first input/output port. The method

begins by receiving the WDM signal at the first input/output port. Next, the first wavelength component is selected from among the plurality of wavelength components. A given input/output port is selected from among any of the plurality of input/output ports. The first wavelength component is directed to the given input/output port. In addition, the second wavelength component is directed to another given one of the plurality of input/output ports, which is selected independently from the given input/output port to which the first wavelength component is directed.

Brief Description Of The Drawings

FIG. 1 shows the functionality to be achieved by an optical switching fabric constructed in accordance with the present invention.

FIG. 2 illustrates a broadband, wavelength-independent optical switch constructed in accordance with the present.

FIG. 3 illustrates a wavelength-dependent optical switch constructed in accordance with the present invention.

FIG. 4 illustrates an optical switching fabric constructed of conventional 1xM switches to perform the functionality depicted in FIG. 1.

FIG. 5 shows an embodiment of the invention similar to that shown in FIG. 2 but which employs a correcting lens to enable the switching of expanded beams with minimal insertion loss.

FIG. 6 shows an alternative embodiment of the invention shown in FIG. 5 in which a focusing mirror is used to reduce insertion loss.

FIG. 7 shows another alternative embodiment of the invention.

FIG. 8 shows an alternative embodiment of the invention in which the optically transparent substrate is arranged in a hexagonal configuration.

Detailed Description

FIG. 1 shows the functionality to be achieved by an optical switching fabric constructed in accordance with the present invention. A wavelength division multiplexed (WDM) optical signal is received on one of the ports 69_1, 69_2, … 69_n.

Ports 69_1, 69_2, ... 69_n are bi-directional ports and therefore each can serve as input or output ports. Optical switching fabric 62 is designed to direct the individual wavelength components of the WDM signal from the receiving port to any select ones of the ports 69_1, 69_2, ... 69_n, including the port that initially received the optical signal. That is, switching fabric 62 can selectively direct any wavelength component from any input port to any other port, independent of the routing of the other wavelengths. Accordingly, in contrast to other switching fabrics, this switching fabric does not have two distinct subsets of ports, one serving as input ports and the other serving as output ports.

It should be noted that the term wavelength component as used herein should not only be construed as limited to a single wavelength. Rather, the term wavelength component may also refer to a band of wavelengths. That is, a wavelength component can refer to a single wavelength or a waveband (such as provided by a contiguous set of channels) which defines a subset of the total waveband encompassed by the WDM optical signal.

FIG. 2 illustrates a broadband, wavelength-independent embodiment of the invention. In FIG. 2, lens 321 and tiltable mirror 315 act as an assembly to retroreflect an incoming beam 350 received from an array of ports (not shown), each of which may comprise a collimating lens and an optical fiber. The spatial location of the retroreflected beam 352, which is parallel to incoming beam 350, is determined by the tilt angle of the mirror 315. As is evident from FIG. 2, an incoming beam received from a given port can be directed to any other port. Notably, if the mirror 315 is tilted so that incoming and retroreflected beams 350 and 352 are coincident, the incoming beam can even be directed back to the port from which it originated.

It should be appreciated that although in FIG. 2 tilt and translation is only shown in one dimension within the plane of the page, two dimensional switching can be achieved by further tilting the mirror into or out of the page. Additional details concerning the tiltable mirrors will be provided below in connection with the embodiment of the invention shown in FIG. 3.

FIG. 3 illustrates a second, wavelength dependent embodiment of the invention. In FIG. 3, the optical switching element 300 comprises an optically transparent substrate 308, a plurality of dielectric thin film filters 301, 302, 303, and 304, a plurality of collimating lens 321, 322, 323, and 324, a plurality of tiltable mirrors 315, 316, 317, and 318 and a plurality of ports 340_1, 340_2, … 340_n. Substrate 308 has parallel planar surfaces 309 and 310 on which first and second filter arrays are respectively arranged. The first filter array is composed of thin film filters 301 and 303 and the second filter array is composed of thin film filters 302 and 304. Individual ones of the collimating lenses 321-324 and tiltable mirrors 315-318 are associated with each of the thin film filters. Each thin film filter, along with its associated collimating lens and tiltable mirror, effectively forms a narrow band, free space switch, i.e. a switch that routes individual wavelength components along different paths. The overall physical dimensions of switching element 300 will be determined in part by the beam diameter of the WDM signal.

Thin film filters 301-304 are well-known components (for example, see U.S. Patent No. 5,583,683), which have a dielectric multilayer configuration. The thin film filters 301-304 have a wavelength dependent characteristic, that is, their reflectivity and transmissivity depends on the wavelength of light. In particular, among the wavelength components of the WDM optical signal received by thin film filter 301, only the component with wavelength λ_1 is transmitted therethrough. The remaining wavelength components are all reflected by thin film filter 301. Likewise, thin film filter 302 transmits only the component with wavelength λ_2 and reflects all other wavelengths. In the same manner, the thin film filters 303 and 304 transmit components with wavelengths λ_3, and λ_4, respectively, and reflect all other wavelengths. Thus, the present invention demultiplexes wavelengths through a plurality of thin film filters with different pass bands.

The tiltable mirrors 315-318 are any mirrors that can be precisely tilted on 2 axes, and which preferably are very small and reliable with a flatness better than about $\lambda/20$. The exemplary mirrors discussed herein are supported by one or more flexure arms that employ a micro-electromechanical system (MEMS). Actuation of the flexure arms tilts the mirror surface to alter the direction of propagation of an

incident beam of light. Examples of such micro-electromechanical mirrors are disclosed in U.S. Patent No. 6,028,689 and the references cited therein. Of course, other mechanisms may be alternatively employed to control the position of the mirrors, such as piezoelectric actuators, for example.

In operation, a WDM optical signal composed of different wavelengths λ_1, λ_2, λ_3 and λ_4 is directed from one of the ports 340_1, 340_2, ... 340_n to the collimator lens 314_1, 314_2, ... 314_n associated with that port. The WDM signal traverses substrate 308 and is received by thin film filter 301. According to the characteristics of the thin film filter 301, the optical component with wavelength λ_1 is transmitted through the thin film filter 301, while the other wavelength components are reflected and directed to thin film filter 302 via substrate 308. The wavelength component λ_1, which is transmitted through the thin film filter 301, is converged by the collimating lens 321 onto the tiltable, reflective mirror 315. Analogous to the embodiment of the invention shown in FIG. 2, tiltable mirror 315 is positioned so that wavelength component λ_1, which is received by the collimating lens 321 along path 350, is retroreflected from the mirror 315 to a selected one of the ports 340_1-340_n via path 352. Optical path 352 is offset from optical path 350 so that wavelength component λ_1 is directed to the desired port. The particular port that is selected to receive the wavelength component will determine the particular orientation of the mirror 315. If optical paths 350 and 352 are coincident, wavelength component λ_1 will be directed back to the port from which it originated.

As mentioned, the remaining wavelength components λ_2, λ_3, and λ_4 are reflected by thin film filter 301 back into substrate 308 and directed to thin film filter 302. Wavelength component λ_2 is transmitted through thin film filter 302 and lens 322 and retroreflected to a selected port by tiltable mirror 316 via thin film filter 301, which reflects wavelength component λ_2. Similarly, all other wavelength components are separated in sequence by the thin film filters 303-304 and subsequently reflected by tiltable mirrors 317-318 to selected ports. By appropriate actuation of the tiltable mirrors, each wavelength component can be

directed to a port that is selected independently of all other wavelength components. Any wavelengths that have not been redirected by any of the tiltable mirrors may be received by an optional bypass port or fiber 343. Although the embodiment of FIG. 3 is configured to selectively switch four wavelengths, it will be recognized that the invention more generally may selectively switch any number of wavelengths by employing a corresponding number of narrow band, free space switches.

A number of important advantages are achieved by the embodiment of the invention shown in FIG. 3. For example, there is no need to designate a set of input ports that are distinct from a set of output ports. Rather, each of the ports can simultaneously serve as an input port or an output port. Additionally, because free space switching is employed, the number of optical connections is kept to a minimum, reducing the insertion loss, complexity and cost of the device.

The following description sets forth for illustrative purposes only one particular example of the embodiment of the invention shown in FIG. 3. In this example, the substrate is a rectangular silica block having a thickness of 12 mm, a width of 11.475 mm and a length of 32 mm. A 2x10 array of collimated beams is oriented at an angle of 11.56° with respect to the normal to the block. The array is properly oriented by rotating the beams along an axis parallel to the long dimension of the block to form the desired angle between the block and the array. Individually collimated single fiber output ports are aligned so that the beams in the array are parallel to one another. The focal length of the collimating lenses in the array is chosen such that light exiting a Corning SMF-28™ fiber and passing through a single lens results in an optical beam with a width of 0.45 mm and a Gaussian waist located 72 mm from the lens. The fiber ends are polished flat and have an anti-reflective coating.

The first and second array of narrow band free-space switches each include eight thin film filters. The thin film filters are each a three-cavity resonant thin film filter with a radius of curvature of the filter surface >100m and dimensions of 3.2 mm by 11.2 mm. In the first array, the first thin film filter, which is located 3.2 mm from the edge of the substrate, is bonded with optical-quality, index matching

epoxy to the substrate and has a passband centered at 194.0 THz (1545.32 nm). The optical passband is nominally 0.4 nm wide at -0.5 dB down from the peak, with an isolation of better than –15 dB starting 0.8 nm from the center wavelength. A 12 mm focal length aspheric lens is bonded to the thin film filter. A commercially available, micro-electro-mechanical (MEMS) tiltable mirror is then positioned at the focal point of the lens. Voltages can be applied to the tiltable mirror to vary its angular orientation along two axes. The angles over which the mirror is adjusted typically do not exceed 20°.

The first array also includes a second narrow band free-space switch located 3.23 mm from the first free-space switch. The thin film filter employed in this switch has a center optical wavelength of 193.8 THz (1546.92 nm). Six additional narrow band free-space switches are located along the substrate, which have center wavelengths of 1548.52 nm, 1550.12 nm, 1551.72 nm, 1553.32 nm, 1554.92 nm, and 1556.52 nm, respectively. The center-to-center distance between each subsequent switch is 3.23 mm.

The second array of narrow band free space switches is located on the substrate surface opposing the substrate surface on which the first array of switches is located. The second array of switches, which are also located 3.23 mm apart from one another, are laterally oriented half way between the first array of switches. The eight thin film filters employed in the second array of switches have center pass band wavelengths of 1544.52 nm, 1546.12 nm, 1547.72 nm, 1549.32 nm, 1550.92 nm, 1552.52 nm, 1554.12 nm, and 1555.72 nm, respectively.

Each individual tiltable mirror has an electronics circuit to which a voltage is applied to steer the mirror. The voltage necessary to steer the mirror so that the wavelength it reflects is directed to a particular output fiber will differ from mirror to mirror. The operating voltages (typically over a -60 to + 60 volt range) for steering the mirror are chosen to maximize the optical power coupled into the desired output fiber.

One of ordinary skill in the art will recognize that each of the narrow band free space switches shown in FIG. 3 do not necessarily require a single lens and mirror combination to perform retroreflection. Rather, other combinations of

optical elements may be used to properly redirect the wavelength components. For example, two tiltable mirrors may be arranged to achieve the same result without the use of a lens. Alternatively, a single mirror may be used if in addition to being tiltable along two axes its position can also undergo a spatial translation. This invention may employ any free space switch configuration that can retroreflect the beam with sufficient translation to access the desired fiber ports.

It is often important to monitor the presence and intensity of each individual wavelength component received by the switch shown in FIG. 3. This can become particularly difficult using conventional fiber monitoring taps when the WDM signal includes a large number of wavelength components. In the present invention, this problem may be readily overcome since only a single wavelength component is received by each of the tiltable mirrors. Accordingly, individual wavelength components may be monitored by placing a detector behind the mirror so that it receives the small portion of the power of the wavelength component that passes through the mirror. This information combined with conventional tap monitoring can provide network control and administration a more complete monitoring picture of light routed through the switch.

It is also important to maintain accurate alignment between the tiltable mirrors in their various positions and the input and output fibers to optimize the power they receive from the mirrors. This can be accomplished by slow adjustment of the mirrors while monitoring the power coupled to the fiber via conventional fiber monitoring taps. However this approach becomes complicated if many other wavelengths are present on the fiber, in which case it may be useful to improve the detection of each wavelength component by encoding a small amplitude modulation with a unique RF frequency that is detected at the respective output fibers while adjusting the positions of the tiltable mirrors. This RF tone can be encoded at the transmitter with a unique tone for every wavelength, or alternately the RF amplitude modulation can be temporarily encoded during mirror adjustment by providing a small oscillation of the mirror tilt that slightly changes the coupling efficiency to the fiber. The latter approach is beneficial in tones that are encoded where they are measured, eliminating the need to track them throughout the

network, and additionally, the tones are only encoded when they are needed for adjustments.

Another embodiment of the invention will now be described with reference to FIGS. 1 and 4. Similar to the embodiment shown in FIGS. 2 and 3, this embodiment has no predefined input or output ports. Unlike the embodiments in FIGS. 2 and 3, however, this embodiment employs conventional 1xM optical switches and multiplexers. Referring to FIG. 1, a WDM signal is received on any of the input/output ports 69_1, 69_2, ...69_n and is demultiplexed into individual wavelength components or channels output onto individual fibers using conventional demultiplexers 67_1, 67_2, ...67_n. Such demultiplexers are well known and can be fabricated from any of several different technologies, including, but not limited to, thin film dielectric filters and arrayed waveguide gratings in silica optical waveguides. Each individual switching fabric 65_1, 65_2, ...65_n receives the same wavelength component from all of the demultiplexers 67_1, 67_2, ...67_n. For the given wavelength component that it receives, the switching fabric can establish a bi-directional optical connection between any two of the input/output ports 69_1, 69_2, ...69_n, thereby enabling an incoming signal to be directed from the switching fabric to any of the demultiplexers 67_1, 67_2, ...67_n. The demultiplexers will in turn multiplex the signal with any other wavelength components received from the other switching fabrics 65_1, 65_2, ...65_n. If an independent switching fabric is available for each and every individual wavelength component or channel, any component of a WDM signal can be routed between any of the input/output ports 69_1, 69_2, ...69_n, independent of the routing of the other components.

FIG. 4 shows an example of one of the switching fabrics 65_1, 65_2, ...65_n. In FIG. 4, an incoming wavelength from any of the input/output ports enters the unique input port 61_1, 61_2, ...61_n of one of the conventional 1xM switches 63_1, 63_2, ...63_n. All but one of the M output ports of switches 63_1, 63_2, ...63_n are connected to each of the other 1xM switches. The remaining output port of each switch 63_1, 63_2, ...63_n is coupled to a mirror 60 that reflects the wavelength back to the input port of that switch. Since a connection can be made in this fashion between any two desired 1xM switches, optical signals can clearly be routed between any two

input ports 61_1, 61_2, ...61_n of the switching fabric, including reflection out the incoming port. An incoming wavelength received on the input port of any given 1xM switch can be routed by that given switch to a desired one of the input/output ports 69_1, 69_2, ...69_n (FIG. 1) by establishing a connection from the given 1xM switch to the 1xM switch connected to the demultiplexer associated with the desired input/output port. The demultiplexer, in turn, will multiplex the wavelength onto the desired input/output port.

Returning to the embodiments of the invention shown in FIGS. 2 and 3, in some circumstances an optical beam entering the switches of FIGS. 2 or 3 is not adequately collimated. As a result, a free space switch (whether broad band or narrow band) formed from a simple aspheric lens and a tiltable mirror located at the focal plane of the lens will introduce insertion loss when the switch directs light back to one of the input/output ports. This loss arises because while a beam received from any given port will cross the optical axis of the aspheric lens at the focal point, its beam waist will not be located in the focal plane. As shown in FIG. 5, a correcting optic 54 can be inserted between the aspheric lens 50 and the tiltable mirror 52 to minimize this contribution to the insertion loss. The correcting optic 54 may be, for example, a convex-concave lens with surfaces having a spherical radius of curvature equal to the distance from the surface to the tiltable mirror 52. In this manner, the correcting optic 54 does not steer an optical beam, but simply changes the position of its beam waist. In this way it is possible to locate the waist of every beam in the focal plane while ensuring that each beam crosses the optical axis in the focal plane. Alternatively, instead of incorporating correcting optic 54 into each of the free space switches, one of the free space switches may be replaced with a focusing mirror. For example, as shown in FIG. 6, optical element 850 is an array of focusing mirrors rather than a free space switch. While focusing element 850 is shown located in the optical path between free space switches 840 and 860, the element 850 more generally may be located in the optical path between different ones of the free space switches. Focusing element 850 adjusts the location of the beam waist to maintain the collimation of relatively small beams in the switching fabric within their Rayleigh range. Maintaining this

level of collimation in turn obviates the need for the focal point correction as discussed in connection with FIG. 5.

FIG. 8 shows one alternative embodiment of the invention in which optically transparent substrate 608 is arranged in a nearly circular configuration. Of course, as with the previous embodiments of the invention, the substrate 608 may be ambient air, silica glass, or some other optically transparent medium. In this way each of the tiltable mirrors 615-621 may be arranged in a circular configuration about the substrate 608. One advantage of this arrangement is that the distance between each tiltable mirror can be increased relative to the distance between each tiltable mirror in the embodiment of the invention shown in FIG. 3. Since more space is now available, the additional distance provides more flexibility in the configuration of the packaging that houses the tiltable mirrors. For example, the extra space may allow off-the-shelf tiltable mirror packages to be employed without being customized to reduce their size.

FIG.7 shows another alternative embodiment of the invention in which two or more individual ones of the inventive optical switches 300 shown in FIG. 3 are used to provide an extended-wavelength switch 700 that can route more wavelength components than either of the individual switches 300. This may be an advantageous way to extend the wavelength capabilities of an individual switch fabric to avoid the collimation problems discussed in connection with FIG. 5 and FIG. 8. In particular, if individual switch 710 is configured to route wavelengths λ_1-λ_8 and individual switch 720 is configured to route wavelengths λ_9-λ_{16}, then the extended-wavelength switch 700 can route wavelengths λ_1-λ_{16} in the same manner as an individual switch 300 that is configured to route wavelengths λ_1-λ_{16}. In addition to individual switches 710 and 720, extended wavelength switch 700 includes a banding filter 730 and prism 740. Filter 730 may be a thin film filter similar to thin film filters 301-304 shown in FIG. 3. Filter 730 is configured so that it transmits wavelength components λ_1-λ_8 and reflects wavelength components λ_9-λ_{16}. Filter 730 is positioned to receive a WDM signal from input/output ports 740_1, 740_2, … 740_n. Accordingly, wavelength components λ_9-λ_{16} are reflected to switch 720, which routes the components in the same manner as discussed in connection

with FIG. 3. Likewise, wavelength components λ_1-λ_8 are transmitted through banding filter 730 and reflected by prism 740 in accordance with the principles of total internal reflection to switch 710. While FIG. 7 shows an extended-wavelength switch formed from two individual switches 300 transited in parallel, those or ordinary skill in the art will recognize that any number of individual switches 300 may be concatenated in a similar manner to route any desired number of wavelength components.